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13. ABSTRACT (Maximum 200 words) This project produced advances in the theory of wavelets and two-channel filter banks, and the development of new algorithms for the generation of wavelet filters and the wavelet based processing of image data, with a view towards their usefulness in image analysis for target recognition. These results include implementation of simulated annealing and Discrete Wavelet Transform algorithms, derivation of parameterizations for various useful spaces of wavelets, derivation of expressions for frequency and spatial uncertainty in wavelets, generation of wavelets optimized for different balances between spatial and frequency uncertainties, and development of wavelet transform domain denoising algorithms for feature detection algorithms.  Much of the research was done on-site at the Naval Surface Warfare Center, Dahlgren, VA. Several collaborations were formed with NSWC scientists, and these produced accomplishments in addition to those in the grant proposal. Also, the P.I. presented tutorial courses and seminars to NSWC personnel. Some of the research was performed during visits to universities in South Africa, resulting in further useful and on-going collaborations.  The grant supported a total of 6 graduate students (one Doctoral and 5 Masters) who performed software development and some theoretical derivations. During the period of the grant, 13 peer-reviewed papers were published (3 in journals and 10 at conferences).				
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## **Final Progress Report on ONR Grant N000149910091**

**Title: Wavelet-Based Feature Extraction for Target Recognition and Minefield Detection**

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### **1. Summary**

This project produced advances in the theory of wavelets and two-channel filter banks, and the development of new algorithms for the generation of wavelet filters and the wavelet based processing of image data, with a view towards their usefulness in image analysis for target recognition. These results include implementation of simulated annealing and Discrete Wavelet Transform algorithms, derivation of parameterizations for various useful spaces of wavelets, derivation of expressions for frequency and spatial uncertainty in wavelets, generation of wavelets optimized for different balances between spatial and frequency uncertainties, and development of wavelet transform domain denoising algorithms for feature detection algorithms.

Much of the research was done on-site at the Naval Surface Warfare Center, Dahlgren, VA. Several collaborations were formed with NSWC scientists, and these produced accomplishments in addition to those in the grant proposal. Also, the P.I. presented tutorial courses and seminars to NSWC personnel. Some of the research was performed during visits to universities in South Africa, resulting in further useful and on-going collaborations.

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## **2. List of Research Accomplishments:**

The following work described in the proposal has been completed:

### **Task 1**

1. Implementation of simulated annealing algorithm in Matlab
2. Implementation of simulated annealing algorithm in C
3. Implementation of Discrete Wavelet Transform in one and two dimensions in Matlab.
4. Implementation of Discrete Wavelet Transform in one and two dimensions in C.
5. Testing and verification of the above algorithms. These algorithms are general, in that they are able to handle arbitrary image sizes, any number of scales, any wavelet function, and various forms of edge reflection.

### **Task 2**

Parameterizations were found for the following spaces of wavelets:

1. orthonormal wavelets (two parameterizations).
2. symmetric complex orthonormal wavelets.
3. symmetric biorthogonal wavelets of odd length.
4. symmetric biorthogonal wavelets of even length.
5. symmetric biorthogonal wavelets of odd length having a specified order of regularity.
6. symmetric biorthogonal wavelets of even length having a specified order of regularity.

Although the parameterizations for (5) and (6) above were derived for the general case, implementations were developed for special cases only.

The P.I. worked with NSWC scientist Dr. Addison Jump to develop a parameterization for orthonormal wavelets of specified regularity. Some useful mathematical expressions governing the regularity of orthonormal wavelets under the parameterizations (1) above were found, but not yet a general solution to this problem.

### **Task 3**

Theoretical expressions were derived for the frequency and spatial dispersions of any FIR filter in terms of the coefficients of its impulse response.

### **Task 4**

1. A wavelet based denoising algorithm was developed and applied to fixed-pixel-location time series extracted from infra-red video imagery of mines in water.
2. The CRITTIR project at NSWC involves the use of a high-resolution infrared camera to capture video sequences over water under sunlit conditions, and to use temporal techniques to detect incoming targets obscured by glare of sunlight on the water. A statistically based algorithm was developed to analyze time series extracted from these video sequences. This algorithm makes a determination of

target present /not present. It was found to improve on the existing algorithm used on CRITTIR.

Marilyn Rudzinsky at NSWC, who runs the CRITTIR project, assisted in the above work by providing video data.

#### **Task 5**

1. By process of simulated annealing, a series of orthonormal wavelet filters was generated, each optimized for a different trade-off between frequency and spatial dispersions (i.e. having 'balanced uncertainty').
2. Optimal orthonormal and biorthogonal wavelets of various lengths were obtained by simulated annealing. The optimality criterion was rms error after wavelet image compression. Various standard test images were used.

**Other results** achieved by the P.I. in addition to work explicitly described in the research proposal are:

1. Refinement of the Discrete Wavelet Transform in one and two dimensions in MATLAB. In the original version of these algorithms, the inverse transform was considerably slower-running than the forward transform. After a detailed analysis of the performance of these algorithms, improvements were implemented which sped up the forward and inverse transforms by factors of 2 and 20, respectively.
2. In collaboration with NSWC scientists Jack Shuler and Ron Tiedge, development of Matlab software to optimize RF absorption characteristics of multilayer rubber surfaces. This optimization is based upon the use of simulated annealing, and makes use of the optimizer developed as item (1) under "Task 1" above.
3. With the assistance of Ron Gross of NSWC, the P.I. developed (in Matlab) a software suite to be used to demonstrate the wavelet based algorithms including some of those produced during the research on this project.
4. Assisted Bryan Freeman of NSWC with his project involving the development of methods for determination of true north without using the earth's magnetic field.
5. Derivation of an algorithm to generate a two-channel perfect-reconstruction filter bank using as the analysis filter any desired filter whatsoever. The algorithm results in a synthesis filter of any desired order of regularity.
6. Generalization of the one-dimensional wavelet transform algorithm to M-band wavelets.
7. Implementation in Matlab of an algorithm that parameterizes all paraunitary M-band filter coefficients.
8. Implementation in Matlab of an algorithm that, given an admissible lowpass filter for a paraunitary M-band filter bank, generates all other filter coefficients in the filter bank.

### **3. Collaborations and Research Visits**

The P.I. visited the Naval Surface Warfare Center, Dahlgren, VA on three occasions (summer 1999, January 2000, and summer 2001) to perform work on this grant.

These visits amounted to a total of 19 weeks.

Collaborations established at NSWC include:

1. Addison Jump, development of parameterizations for orthonormal wavelets.
2. Ron Gross (G33), development of Matlab demonstration suite for wavelet algorithms.
3. Jack Shuler (G33) and Ron Tiedge, development of Matlab software to optimize RF absorption characteristics of multilayer rubber surfaces.
4. Bryan Freeman (G33), non-magnetic determination of true north using gyroscopes.
5. Marilyn Rudzinsky, clutter rejection involving temporal techniques in the infrared.

The P.I. visited the University of Stellenbosch and the University of Cape Town, South Africa for a total of 23 weeks to perform work on this grant. These Universities provided financial assistance towards travel and accommodation. Collaborations were developed that were valuable for the work on this grant. There are also promising possibilities for attracting outstanding doctoral students to UNC-Charlotte study under the P.I. The following collaborations have been established:

1. Dr. Gerhard De Jager, Professor of Signal Processing in the Department of Electrical Engineering at the University of Cape Town.
2. Dr. Johan Du Preez, Professor of Signal Processing in the Department of Electrical Engineering at the University of Stellenbosch.
3. Dr. Ben Herbst, Professor of Applied Mathematics at the University of Stellenbosch.

Drs. De Jager and Du Preez are experts in pattern recognition, an expertise that is useful to the P.I. in applying his knowledge of wavelet theory and signal processing to problems involving target recognition. Dr. Herbst is an accomplished applied mathematician whose insight is valuable in finding solutions to problems in wavelet theory upon which the P.I. is engaged. Plans are in place to obtain funding from the South African Foundation for Research Development to obtain funding for their doctoral students to visit UNC-Charlotte, further developing the relationship between the P.I. and these institutions.

A collaboration between the P.I. and Dr. Y.P. Kakad, Professor of Electrical and Computer Engineering at the University of North Carolina-Charlotte has been established. Dr. Kakad provides expertise concerning the hardware implementation of algorithms developed by the P.I. Several publications produced by this collaboration are listed later.

#### 4. Students:

The following graduate students performed work on this project during the period covered by this report:

1. **Steven Moore**, Ph.D. (Elec. Eng.) student. It was originally intended that the work in this grant would form the subject of Mr. Moore's Ph.D. research work. However, Mr. Moore had to leave UNC-Charlotte for personal reasons after one year.

2. **Leroy A. Calder**, M.S.E.E. student, developed Matlab software in support of the research work of the PI.
3. **Kevin L. Conrad**, M.S.E.E. student, developed wavelet transform software in C++.
4. **Osama Abu-Sharkh**, M.S.E.E. student, assisted with the derivation of fast transform algorithms.
5. **M. Goberu**, M.S. Computer Science student, developed algorithms for the rapid real-time update of discrete cosine transforms.
6. **Parinita Rane**, M.S. Computer Science student, developed software for transform algorithms.

Because of Mr. Moore's departure, it was possible to support the Masters students instead.

## 5. Publications:

The following refereed journal and conference papers were published by the P.I. during the period of the grant:

1. B.G. Sherlock and Y.P.Kakad, "Windowed Discrete Cosine and Sine Transforms for Shifting Data", *Signal Processing*, Vol. 81, July 2001, pp. 1465-1478.
2. B.G. Sherlock and Y.P.Kakad, "Transform Domain Technique for Windowing the DCT and DST", *Journal of the Franklin Institute* Vol. 339, No. 1, 2002, pp. 111-120.
3. B.G. Sherlock, "Windowed Discrete Fourier Transform for Shifting Data", *Signal Processing*, Vol. 74, 1999, pp. 169-177.
4. H.H. Mu, Y.P. Kakad and B.G. Sherlock, "Design of control systems using neural networks", *17<sup>th</sup> Annual Conference on CAD/CAM, Robotics and Factories of the Future (CARS&FOF'2001)*, Durban, South Africa, July 10-12, 2001.
5. B.G. Sherlock and Y.P. Kakad, "Real Time Rapid Update of Type-I DCT and DST for Moving Window", *8<sup>th</sup> International Conference on Advances in Communication and Control (COMCON 8)*, Crete, Greece, 25 - 29 June 2001.
6. A. Jump and B.G. Sherlock, "Simplified equations to generate wavelets of arbitrary order of regularity", *SPIE 15th Annual International Symposium on Aerospace/Defense Sensing, Simulation, and Controls (Aerosense 2001)*, Orlando, Florida, April 2001. Published in *Proceedings of SPIE*, Volume 4391.
7. B.G. Sherlock and Y.P. Kakad, "Rapid update of discrete Fourier transform for real-time signal processing", *SPIE 15th Annual International Symposium on Aerospace/Defense Sensing, Simulation, and Controls (Aerosense 2001)*, Orlando, Florida, April 2001. Published in *Proceedings of SPIE*, Volume 4379.
8. Y.P. Kakad and B.G. Sherlock, "Rapid prototyping of update algorithm of discrete Fourier transform for real-time signal processing", *SPIE 15th Annual International Symposium on Aerospace/Defense Sensing, Simulation, and Controls (Aerosense 2001)*, Orlando, Florida, April 2001. Published in *Proceedings of SPIE*, Volume 4379.

9. H.H. Mu, Y.P. Kakad and B.G. Sherlock, "Artificial neural network based controller design for advanced aircraft", *14th International Conference on Systems Engineering (ICSE 2000)*, Coventry, England, September 2000.
10. B.G. Sherlock and Y.P.Kakad, "Windowing the Discrete Cosine Transform in the Transform Domain", *4<sup>th</sup> World Multiconference on Circuits, Systems, Communications and Computers (CSCC'2000)*, Athens, Greece, July 2000 (paper number 126).
11. Hong Helena Mu, Y.P. Kakad and B.G. Sherlock, "Application of Artificial Neural Networks in the design of Control Systems", *16<sup>th</sup> Annual Conference on CAD/CAM, Robotics and Factories of the Future (CARS&FOF'2000)*, Trinidad, June 2000
12. A.B. Jump and B.G. Sherlock, "Wavelets of Arbitrary Order of Regularity", *SPIE 14<sup>th</sup> Annual International Symposium on Aerospace/Defense Sensing, Simulation, and Controls (AeroSense 2000)*, Orlando, Florida, April 2000. Published in *Proceedings of SPIE*, Volume 4056.
13. B.G. Sherlock and Y.P. Kakad, "Windowed Discrete Cosine Transform for Shifting Data", *3<sup>rd</sup> IMACS/IEEE International Multiconference on Circuits, Systems, Communications and Computers (CSCC'99)*, Athens, Greece, July 1999.

## 6. Presentations:

1. The P.I. developed a two-day course entitled "Wavelets and Filter Banks" that provides an intensive introduction to the theory and applications of wavelet analysis. This course was presented three times (1998, 1999, and 2001) at the Naval Surface Warfare Center in Dahlgren, VA to research scientists. This course resulted in much favorable feedback and led to further collaborative work between the P.I. and NSWC research staff who attended the course.
2. "The Chirp z-Transform", tutorial seminar presented at the Naval Surface Warfare Center, Dahlgren, VA, June 1999.
3. "Independent Component Analysis", tutorial seminar presented at the University of Stellenbosch, South Africa, July 2001.